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Interactions of traffic and tillage applied to cotton on N movement below the root zone of a subsequent wheat crop

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Abstract

Although research has demonstrated the negative impact of traffic-induced soil compaction on crop productivity, knowledge is lacking regarding the interactive effects of equipment traffic and tillage systems, especially in regards to N management in conservation-tilled multiple-cropping systems. The objective of this study was to examine the interaction of traffic and tillage systems applied to cotton (*Gossypium hirsutum* L.) on N utilization and movement below the root zone of subsequent double-cropped wheat (*Triticum aestivum* L.). A field study was initiated in 1987 on a thermic Typic Hapludult soil complex, utilizing a wide-frame tractive vehicle (WFTV) that allows for 6.1-m wide, untrafficked research plots to double-crop cotton with wheat. The experimental design was a split-plot with three replications. Main plots were: (1) conventional traffic (simulated with tractor); (2) no traffic (WFTV only). Subplots were tillage systems for cotton: (1) complete surface tillage without subsoiling (surface); (2) complete surface tillage and annual in-row subsoiling to 40-cm depth (subsoil); (3) complete surface tillage with once-only complete disruption of the tillage pan by subsoiling to a 50-cm depth on 25-cm centers in 1987 (complete); (4) strip-till where cotton was planted with in-row subsoiling into wheat residue. All tillage treatments were applied to the cotton and residual effects were observed in the wheat. In 1990–1991, fertilizer applications were made to wheat as ^{15}N-labeled NH_4NO_3, and soil solution samples were collected (90-cm depth). While previous cotton tillage had no significant effect on wheat yields, traffic reduced wheat yields from 3427 to 2981 kg ha^{-1} in 1990. With no traffic, total fertilizer N recovery in the plant–soil system was increased by 20 and 10% in 1990 and 1991, respectively. The strip-till tillage treatment increased total fertilizer N recovery in wheat by 20% compared with other tillage systems in 1990. Surface tillage without subsoiling for cotton increased NO_3-N con-

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centration below the root zone of wheat (90-cm depth) in both years. The data indicate that the tillage/traffic management system used for production of one crop in a double-cropping system was a major factor in reducing N losses and increasing fertilizer N recovery in the plant–soil system of the succeeding crop.

Keywords: ^{15}N; *Gossypium hirsutum* L.; *Triticum aestivum* L.; Compaction; Strip tillage; Subsoiling

1. Introduction

Soil compaction has been recognized as a major crop production problem because of its effects on reduced plant root proliferation and lower rates of water and air movement through the soil. This has been demonstrated especially on sandy coastal plain soils of the southeastern USA (Chancy and Kamprath, 1982; Box and Langdale, 1984; Reeves et al., 1992). Reduced N uptake caused by physical impedance and stress on plant roots (Castillo et al., 1982; Garcia et al., 1988), and alterations of soil N transformation processes (Bakken et al., 1987; Håkansson et al., 1988; Torbert and Wood, 1992) have also been attributed to soil compaction. For example, soil compaction alteration of soil pore spaces was found to promote soil microsite anaerobiosis, resulting in increased denitrification (Torbert and Wood, 1992). Likewise, in field measurements, soil compaction led to a three- to four-fold increase in N losses via denitrification (Bakken et al., 1987).

The effect of soil compaction caused by wheel traffic may be very persistent, especially in the subsoil (Boone, 1988; Håkansson et al., 1988). For example, increased bulk density and reduced hydraulic conductivity caused by traffic persisted after 4 years (Voorhees et al., 1986), while subsoil compaction in terms of increased bulk density persisted 9 years after treatment application (Blake et al., 1976).

Research has shown that tillage systems strongly affect both N losses and N uptake by plants (Moschler and Martens, 1975; Tyler and Thomas, 1977; Meisinger et al., 1985; Gilliam and Hoyt, 1987). Conservation tillage systems, for example, have been reported both to increase soil N concentrations as a result of immobilization (Gilliam and Hoyt, 1987) and to increase N losses from both leaching (Tyler and Thomas, 1977) and denitrification (Gilliam and Hoyt, 1987). Factors such as soil moisture and temperature, which are dependent on tillage systems, may lead to changes in N efficiency (Jansson and Persson, 1982).

The fate of fertilizer N applied to agricultural soils is of growing concern because of the potential for groundwater contamination and health risks associated with high nitrate levels in groundwater. Application of fertilizer N to agricultural soils has been implicated in causing non-point pollution of groundwater (US Environmental Protection Agency, 1990). In addition to potential environmental problems associated with nitrate leaching, the economic impact on the farmer can be considerable. Nitrogen is the most expensive cash input for non-legume crops, and the loss of this nutrient means reduced profitability.

While much research has focused on the effect of tillage systems on N fertility, little research has been conducted to study the interaction of equipment traffic and tillage systems on N losses and recovery. This is especially true in conservation tillage systems and multiple-cropping systems. Additionally, because of the persistent nature of traffic-caused soil compaction, an understanding is needed of how tillage and traffic influence N management of subsequent crops. Understanding changes in plant–soil–N interactions brought about by tillage and traffic will be critical to the management of N fertilizers for both profitable and environmentally sound agricultural systems. Thus, the objective of this study was to examine the interaction of traffic and tillage systems applied to cotton on N utilization and movement below the root zone of subsequent double-cropped wheat.

2. Materials and methods

A field study was initiated in June 1987 at the Alabama Agricultural Experiment Station's E.V. Smith Research Center in east-central Alabama, USA. The soil is a Cahaba–Wickham–Bassfield sandy loam complex. The Cahaba soil is a fine loamy, siliceous, thermic Typic Hapludult. The Wickham soil is a fine loamy, mixed, thermic Typic Hapludult. The Bassfield soil is a coarse loamy, siliceous, thermic Typic Hapludult. Cation exchange capacity (CEC) and organic matter content for the test site averaged 6.31 $cmol_c\ kg^{-1}$ and 11.9 $g\ kg^{-1}$, respectively. The site naturally has a well developed 8- to 15-cm-thick hardpan, beginning at a depth ranging from 20 to 30 cm. To reduce variation due to depth, an effort was made to form a uniform hardpan at a depth of 20 cm by repeatedly running a motor grader in plowed furrows incrementally across the experiment site in the fall of 1986.

This study utilized a wide-frame tractive vehicle (WFTV) which spans a 6.1-m wide area, allowing all tractor traffic to be kept off the plots. Detailed descriptions of the vehicle and its capabilities have been published by Monroe and Burt (1989) and Reeves et al. (1992).

Cotton cultivar 'McNair 220' was grown in a double-cropping system with wheat cultivar 'Coker 9733'. The development of early maturing cotton and wheat cultivars has made double-cropping these two crops a feasible alternative in the southeastern USA (Baker, 1987). Figure 1 depicts a time line indicating the approximate times for farm operations, treatment applications, and data collection in the study.

The experimental design was a split-plot with three replications. Main plots (6.1 m wide and 183 m long) were: (1) conventional traffic; (2) no traffic. To ensure uniform tillage equipment operation, all operations were performed with the WFTV. On the conventionally trafficked plots, a 4440 John Deere tractor or a high-clearance sprayer was driven through the plots to simulate traffic that would have been applied with each cultural operation. Traffic patterns followed those expected with four-row equipment, with random patterns used to simulate preparation/planting operations for wheat, and uniform patterns used for operations performed during the cotton-growing season.

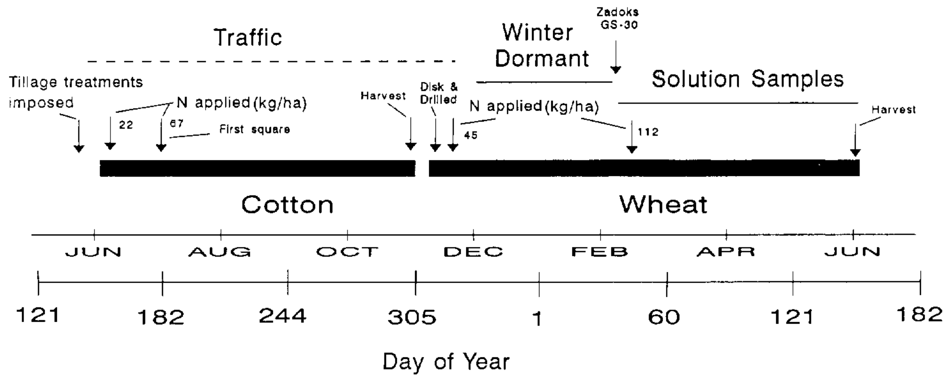

Fig. 1. Time-frame for operations and data collection in cotton-wheat double-cropping experiment. Tillage treatments applied to cotton only: (1) surface tillage without subsoiling; (2) surface tillage and annual in-row subsoiling; (3) surface tillage and once-only complete disruption of tillage pan; (4) no surface tillage and annual in-row subsoiling. Traffic: applied corresponding to all farming operations for both cotton and wheat.

Main plots were split into subplots (37 m long) of tillage systems applied to cotton: (1) complete surface tillage without subsoiling (surface); (2) complete surface tillage and annual in-row subsoiling to 40 cm depth (subsoil); (3) complete surface tillage with once-only complete disruption of the tillage pan (complete); (4) no surface tillage but planted with in-row subsoiling into wheat residue (strip-till). The location of main plots and subplots remained constant throughout the duration of the study. Complete surface tillage consisted of disking, chisel-plowing (20 cm depth), disking, and field cultivation. The once-only complete disruption of the tillage pan was accomplished by subsoiling to 50 cm depth on 25-cm centers, using a V-ripper, in November 1987. The strip-tilled cotton was planted into wheat stubble with an in-row subsoiler planter.

Cotton was planted in eight 76-cm rows at 220 000 seeds ha^{-1}, as close to 1 June each year as possible. Cotton was harvest on approximately 1 November of each year. After the cotton was harvested, all plots were disked and planted to wheat with a 3-m-wide drill having 10 cm drill spacing.

Subplot tillage treatments were imposed on cotton only, with the complete complement of tillage treatments first imposed during the 1988 growing season. A disking operation was performed for all plots prior to planting wheat each year. Therefore, tillage treatment responses observed in wheat were due to tillage application to the previous cotton crop. Recommended cultural practices for insect and weed control were used on all plots throughout the growing season for both crops.

During 1990–91, additional research was initiated to evaluate N dynamics in the wheat component of the double-cropping system as affected by the previous cotton tillage systems and traffic. This research is the focus of this paper. Ammonium nitrate was applied broadcast for both crops. The rate for cotton was 22 kg N ha^{-1} at planting and 67 kg N ha^{-1} at first square (formation of first flower). The rate for wheat was 45 kg N ha^{-1} at planting and 112 kg N ha^{-1} following winter dormancy at Zadoks GS-30 (Zadoks et al., 1974, just prior to stem elongation). The 112 kg N ha^{-1} application was made on Days 58 and 44 of the year in 1990 and 1991, respectively. In the wheat plots, ^{15}N-depleted NH_4NO_3 was applied to a 2.4 m×3 m microplot inside each tillage/traffic subplot. Microplots were rotated to new locations within plots each year.

Soil solution samplers (90 cm depth) were installed in each ^{15}N-depleted wheat microplot. Nitrate in the soil solution was determined using steam distillation techniques (Keeney and Nelson, 1982). Monitoring of soil solution samples for NO_3-N began at approximately the time of the second fertilizer N application (112 kg ha^{-1}) to the wheat. Monitoring began on Days 64 and 43 of the year in 1990 and 1991, respectively, and continued weekly until harvest. This sampling period was chosen because weather patterns in Alabama make this period the most vulnerable to nitrate leaching as well as supplying adequate soil moisture conditions for solution sampling. In addition, this period also follows the largest fertilizer N addition and is the most active for plant N uptake. Water fluxes were not measured and thus N fluxes are not available. Nitrate-N concentrations in soil solutions from below the root zone of wheat are presented over time as an indication of potential N losses between experimental treatments. Because of the environmental concern about fertilizer applications contributing to nitrate levels in groundwater, isotope-ratio analysis was also performed to determine the contribution of fertilizer N to the NO_3-N concentration in soil solution samples (when sufficient samples had been collected).

Soil bulk density, used in calculations of fertilizer N recovery, was determined for each plot from intact soil cores collected to a depth of 90 cm. The term fertilizer N in this manuscript is used to reflect N added to the plant–soil system through fertilizer application. The term total fertilizer N recovery is used to reflect fertilizer N recovered in both the plant and the soil. The term fertilizer N deficit is used to reflect fertilizer N not recovered in the plants or soil (^{15}N applied: $^{15}N_{soil}+{}^{15}N_{plant}$).

A plot combine suspended from the WFTV was used to harvest the plots. At physiological maturity, above-ground plant samples were collected from a 0.5-m^2 section for dry matter determinations, and additional plant samples were collected from microplots. Wheat straw dry matter production in 1990 was calculated from grain yields using a harvest index of 0.42 (Williams et al., 1989) because samples were inadvertently ground before weighing.

Plant samples were dried at 65 °C (until weight loss was complete) and ground in a Wiley mill to pass a 0.44-mm screen. Soil cores were collected from all microplots to a depth of 90 cm. Each core was sectioned into increments from depths of 0–15, 15–30, 30–60, and 60–90 cm. Immediately after collection, the soil samples were frozen for transport to the laboratory. The total N content of both plant and soil samples was determined using a permanganate-reduced iron modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Distillates were concentrated for isotope-ratio analyses, which were performed as described by Mulvaney et al. (1990) using an automated mass spectrometer (Nuclide Model 3-60-RMS, Measurement and Analysis Systems, Bellefonte, PA).[1]

Statistical analysis of data was performed using the ANOVA procedure and means were separated using least significant difference (LSD) at the 10% probability level (Statistical Analysis Systems Institute Inc., 1982). The term trend is used to designate appreciable nonsignificant treatment effects with probability levels above 10%.

3. Results and discussion

A detailed presentation of the effects of tillage and traffic management treatments on soil bulk densities and cone resistances is presented by Raper et al. (1994). In summary, soil bulk densities were reduced with no traffic and with strip tillage. Soil bulk densities averaged 1.28 Mg m^{-3} for no traffic and 1.41 Mg m^{-3} with traffic for strip-till tillage compared with 1.36 Mg m^{-3} with no traffic and 1.48 Mg m^{-3} with traffic for surface tillage.

3.1. Yield and N recovery

Only data for the 1990 and 1991 growing season are reported. In 1990, traffic reduced wheat yield by 16%, with yields being 3.4 and 3.0 Mg ha^{-1} ($LSD_{0.01}=0.3$) for no-traffic and traffic, respectively. This is consistent with results reported by Oussible et al. (1992) of a 12–23% reduction in wheat yield due to subsoil compaction, and those of Bennie and Botha (1986) of a 19% increase in wheat yield with controlled traffic and deep ripping. In 1991, wheat yields were reduced by scab head blight (*Fusarium* spp.) along with a severe thunderstorm, resulting in lodging of the wheat. Consequently, yields were exceptionally low (average 1.2 Mg ha^{-1}) and no significant differences were detected as a result of traffic. Tillage applied to the previous cotton crop had no significant main effect or interaction effect on wheat yield in either year.

Fertilizer N recovery in 1990 was influenced by both tillage and traffic (Tables 1 and 2), but no interactions occurred. In 1990, traffic significantly decreased fertilizer N recovery in both the plant and the soil, resulting in a decrease from 87.8 to 73.2 kg N ha^{-1} in total fertilizer N recovery for no traffic compared to traffic (a 17% decrease, Table 1). For the traffic treatments, a large portion of the decreased fertilizer N recovery in this year can be attributed to decreased plant N uptake (Table 1). In addition, a significantly lower amount of fertilizer N recovered from soil (cumulative to 90 cm deep) was observed for the traffic treatment as compared with the no-traffic treatment, indicating that N losses were smaller with no traffic.

Tillage treatments in 1990 also resulted in differences in fertilizer N recovery

[1] Trade names and products are mentioned solely for information. No endorsement by the US Department of Agriculture is implied.

Table 1
Effect of traffic on fate of fertilizer N at wheat harvest calculated from ^{15}N data in 1990 and 1991[a]

	Fertilizer N ($kg\ ha^{-1}$)	
	No traffic	Traffic
1990		
Total plant uptake	58.3 a	48.2 b
Remaining in soil	29.5 a	25.1 b
Total recovered	87.8 a	73.2 b
N deficit[c]	69.1 a	83.7 b
1991		
Total plant uptake	78.4 a	77.5 a
Remaining in soil	49.9 a	39.2 a
Total recovered[b]	128.3 a	116.7 a
N deficit[c]	28.6 a	40.2 a

[a] Values represent means of three replicates. Values within a row followed by the same letter do not differ significantly (0.10 level) averaged over previous cotton tillage systems.
[b] Probability of greater F value = 0.11.
[c] N deficit calculated by ^{15}N method from fertilizer N applied (157 kg N ha^{-1}) – (total plant fertilizer N + total soil fertilizer $N_{\text{combined 90-cm depth}}$).

(Table 2), with total fertilizer N recovery of 91.2 kg N ha^{-1} for strip till compared with 78.9, 76.0, and 76.0 kg N ha^{-1} for subsoil, surface, and complete tillage treatment, respectively, all of which involved disking and field cultivation. However, there were no significant differences between tillage treatments in the fertilizer N recovered in the plant. Evidently tillage treatments applied to the previous cotton crop resulted in changes in soil N transformations, but did not greatly affect plant response to available N.

In 1991, no significant differences between tillage and traffic treatments occurred (Tables 1 and 2). However, similar to 1990, a strong trend ($P \leqslant 0.11$) occurred for no traffic to increase total fertilizer N recovery compared with traffic (Table 1). As previously discussed, wheat yield in 1991 was not significantly improved by no traffic, resulting in no significant difference in plant fertilizer N. Consequently, the trend in total fertilizer N recovery due to traffic could be attributed to changes in fertilizer N retained in the soil, with traffic decreasing total N fertilizer recovery in the plant–soil system by 10% (Table 1). This was similar to what occurred in 1990.

Since soil bulk density has been shown to increase denitrification losses (Bakken et al., 1987; Torbert and Wood, 1992), much of the difference in fertilizer N recovery between no traffic and traffic may be the result of greater denitrification losses caused by increased compaction in traffic plots (as evidenced by increased bulk density measurements, Raper et al., 1994) during wet periods of the growing season in both years of the study.

Table 2
Effect of previous cotton crop tillage system on fate of fertilizer N (kg ha^{-1}) at wheat harvest calculated from ^{15}N data in 1990 and 1991[a]

Fertilizer N	Tillage system[b]			
	Complete	Strip-till	Subsoil	Surface
1990				
Total plant uptake	53.7 a	57.8 a	50.8 a	50.6 a
Remaining in soil	22.4 b	33.4 a	28.1 ab	25.4 b
Total recovered	76.0 b	91.2 a	78.9 ab	76.0 b
N deficit[c]	80.9 a	65.7 b	78.0 ab	81.0 a
1991				
Total plant uptake	76.3 a	77.6 a	77.2 a	80.8 a
Remaining in soil	46.5 a	48.5 a	39.6 a	43.5 a
Total recovered	122.8 a	126.1 a	116.8 a	124.3 a
N deficit[c]	34.1 a	30.8 a	40.1 a	32.7 a

[a] Values represent means of three replicates. Values within a row followed by the same letter do not differ significantly (0.10 level) averaged over traffic treatments.
[b] Previous cotton tillage: complete = surface tillage with once-only complete disruption of tillage pan; strip-till = no surface tillage but planted with in-row subsoiling; subsoil = surface tillage and annual in-row subsoiling; surface = surface tillage without subsoiling.
[c] N deficit calculated by ^{15}N method from fertilizer N applied (157 kg N ha^{-1}) – (total plant fertilizer N + total soil fertilizer $N_{\text{combined 90-cm depth}}$).

3.2. Soil solution nitrate

Significant differences in the NO_3-N concentration of soil solution samples between traffic and tillage system treatments indicates that NO_3-N leaching might have been a major contributor to N losses. Soil solution NO_3-N increased sharply approximately 12–14 days after the second fertilizer N application in both years (Fig. 2). As the growing season progressed, increased utilization of N resulted in reduced NO_3-N concentration at 90 cm deep in most treatments until near the end of the growing season, when NO_3-N concentration below the root zone began to rise, especially in 1991.

Surface tillage without subsoiling in the cotton resulted in significantly higher NO_3-N concentration at several times in both years (Fig. 2). Because this is the only tillage treatment that did not receive some form of deep tillage, it is believed that compaction-induced root restriction of the wheat resulted in reduced root exploration and N uptake, allowing more NO_3-N to move through the soil profile. Conversely, the subsoiled treatments could have had an increased abundance of deep roots to scavenge for nitrate moving deeper into the soil profile. These results are consistent with work by Long and Elkins et al. (1983), which reported increased removal of nitrate accumulated below the hardpan by cotton in response to increased root penetration below the hardpan in a similar soil.

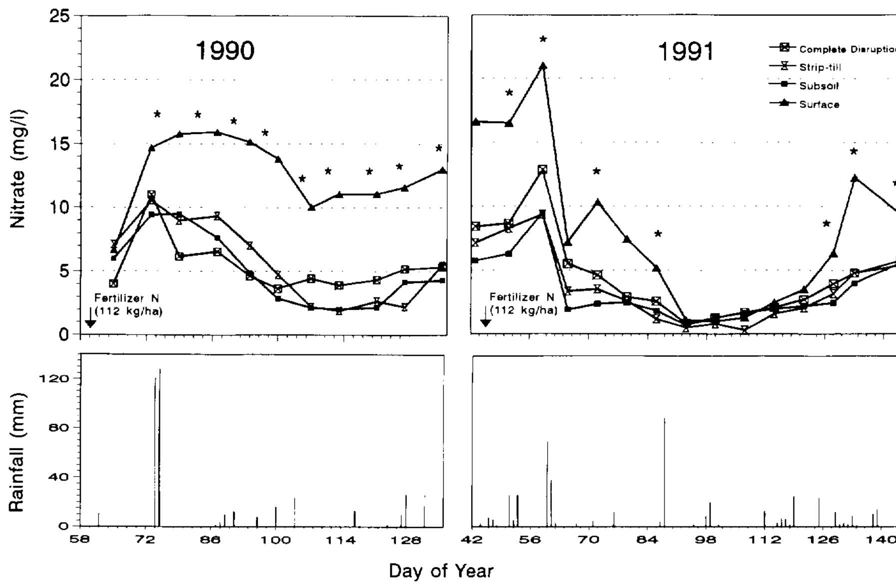

Fig. 2. Soil solution NO_3-N for four tillage treatments imposed on the previous cotton crop, sampled from 90 cm deep during the 1990 and 1991 wheat-growing season. Cotton tillage treatments consisted of: (1) surface tillage without subsoiling (surface); (2) surface tillage and annual in-row subsoiling (subsoil); (3) surface tillage with once-only complete disruption of tillage pan (complete); (4) no surface tillage but planted with annual in-row subsoiling (strip-till). Asterisk denotes dates with significant differences. Means are of four replications, averaged over traffic treatments.

Table 3
Interaction of traffic and previous cotton tillage system on NO_3-N concentration (mg l^{-1}) in soil water at 90-cm depth during 1990 wheat growing season[a]

Day of the year	No traffic				Traffic			
	Surface[b]	Subsoil	Complete	Strip-till	Surface	Subsoil	Complete	Strip-till
79	8.7	9.1	6.0	8.4	22.8	9.8	6.4	9.6
87	7.2	6.8	7.8	9.6	24.7	8.4	5.3	9.1
94	10.2	3.6	2.9	8.4	20.1	6.1	6.3	5.7
104	9.2	3.1	2.3	3.6	18.4	2.6	5.0	2.9

$LSD_{0.10\ (\text{any two means})} = 9.2$; $LSD_{0.10\ (\text{tillage within traffic})} = 8.8$.
[a] Values represent means of three replicates.
[b] Previous cotton tillage: surface = surface tillage without subsoiling; subsoil = surface tillage and annual in-row subsoiling; complete = surface tillage with once-only complete disruption of tillage pan; strip-till = no surface tillage but planted with annual in-row subsoiling.

A significant traffic by tillage interaction was observed for NO_3-N in soil solution in 1990, with traffic causing a large increase in the NO_3-N concentration compared with no traffic within the non-subsoiled surface tillage treatment (Ta-

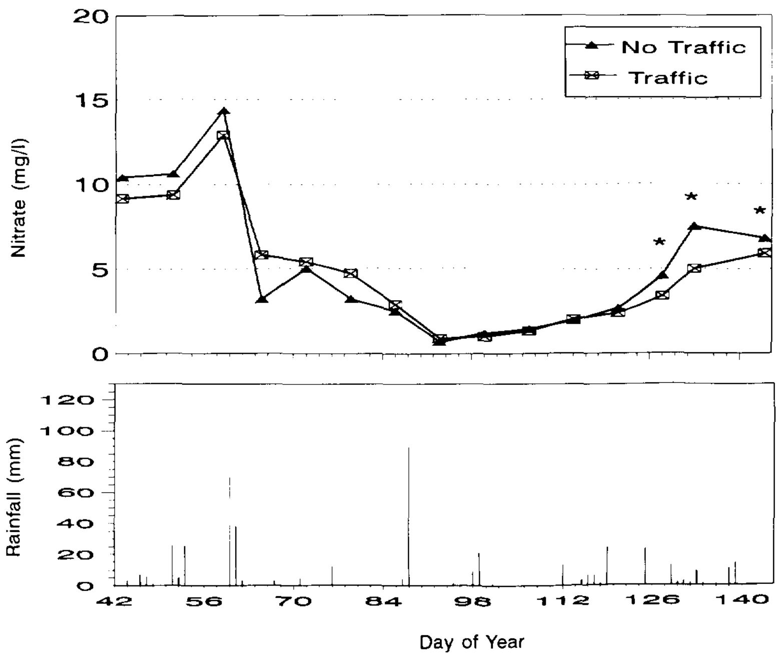

Fig. 3. Soil solution NO_3-N for traffic treatments, averaged over previous cotton tillage treatments, sampled from 90 cm deep during the 1991 wheat growing season. Asterisk denotes dates with significant differences.

ble 3). The most plausible explanation for these data is that traffic-induced soil compaction reduced wheat root development, especially in the treatment receiving no deep tillage (surface tillage). This is supported by penetrometer and bulk density data (not shown here) confirming increased soil strength within the traffic and surface tillage without subsoiling treatment (Raper et al., 1994). Root restriction of wheat could result in reduced N uptake and increased NO_3-N concentration deeper in the soil profile. On Day 79 of the year, a large rainfall event (211 mm) occurred which could have moved a large amount of soil NO_3-N deeper in the soil profile. This speculation is consistent with fertilizer N recovery data for 1990, where recovery was much lower at 0–15 cm deep and much higher at 30–60 and 60–90 cm deep compared with 1991 (data not shown), and also with higher concentrations of NO_3-N in the soil solution through the growing season, especially in treatments where restricted rooting would be expected.

Such a large rainfall event was not repeated in 1991, resulting in a different NO_3-N leaching pattern as affected by tillage treatments (Fig. 2). Similar to 1990, surface tillage resulted in significantly higher concentration of NO_3-N in soil solution at several points, probably as a result of reduced rooting and consequent reduced N uptake. However, concentration of NO_3-N in soil solution for the surface tillage treatment during most of the growing season was lower than in 1990. At the end of the growing season in 1991, when plant senescence would reduce

Table 4
Traffic effect, averaged over tillage treatments, on proportion of NO_3-N in soil water at 90-cm depth attributed to fertilizer N, calculated from ^{15}N data, 1990 and 1991[a]

Day of year	Fertilizer proportion (%)	
	No traffic	Traffic
1990		
65	*	*
73	24.3 a	26.3 a
79	43.8 a	36.6 a
87	45.8 a	33.8 a
94	31.1 a	28.6 a
100	20.1 a	22.2 a
107	*	*
113	*	*
121	*	*
127	*	*
135	*	*
1991		
43	16.5 a	19.4 b
51	13.1 a	20.8 b
59	40.2 a	43.0 a
65	*	*
79	*	*
72	11.0 a	17.5 a
86	*	*
93	*	*
100	*	*
107	*	*
114	*	*
128	13.6 a	7.3 b
133	16.8 a	10.2 a
142	18.2 a	16.3 a

[a]Values represent means of three replicates. Means within the same row followed by the same letter do not differ significantly (0.10 level).
*, insufficient NO_3-N in soil water collected for ^{15}N analysis.

plant water and N use but N mineralization would continue, NO_3-N concentrations increased to levels observed in surface tillage plots in 1990.

Unlike 1990, in 1991 traffic reduced NO_3-N concentration, compared with no traffic, averaged over sampling dates and tillage treatments ($LSD_{0.01} = 1.3$). However, these differences were small and only significant at three sampling dates late in the season after plant senescence (Fig. 3).

3.3. Soil solution isotope analysis

Analysis of the soil solution samples for ^{15}N fertilizer contribution indicated that less than half of the NO_3-N leached could be attributed to the fertilizer N applied to wheat (Table 4). In 1991, variation in the proportion of NO_3-N concentration in soil solution attributed to fertilizer N application also indicated that changes in N transformations resulted from traffic. For example, while traffic caused a significant increase in the proportion of fertilizer N in soil solution during Days 43 and 51, a trend for traffic to decrease the fertilizer N portion in soil solution below the rooting zone occurred at the end of the growing season (Table 4), with a significant reduction at Day 128 and similar tendencies for Days 133 and 142 ($P \leqslant 0.18$). This decrease in the proportion of fertilizer N in soil solution corresponds to the decrease in total NO_3-N concentration in soil solution as a result of traffic discussed previously (Table 4, Fig. 3). These results would be consistent with traffic-induced soil compaction causing decreased infiltration. Håkansson et al. (1988) indicated that soil compaction reduced the number of large soil pores (>30 μm), which can severely reduce infiltration and saturated conductivity. This may account for reduced movement of surface-applied fertilizer through soil on plots with traffic.

Within 17 days of the second fertilizer N application, approximately 25 and 18% of the NO_3-N in soil solution could be attributed to the fertilizer applied to the wheat in 1990 and 1991, respectively (Table 4). In both years, NO_3-N from fertilizer peaked (approaching 50% of total NO_3-N in some treatments) at the same time as total NO_3-N. Afterwards, fertilizer N contribution to NO_3-N concentration decreased to a level generally below 20%. A possible partial explanation of this would be mineralization–immobilization turnover (Jansson and Persson, 1982), where immobilization of fertilizer N increased the proportion of fertilizer N in organic form, and at the same time mineralization of existing soil N in organic form increased the proportion of nonlabeled ^{15}N in soil solution. However, during most of the growing season of both years, the largest proportion of NO_3-N in soil solution was from soil N and not from the application of fertilizer to wheat (^{15}N data). When averaged over all sampling dates, the fertilizer N proportion of NO_3-N in soil solution was 31.5 and 18.4% for 1990 and 1991, respectively.

4. Conclusions

Both traffic and tillage systems affected N recovery and losses in this double-cropping system. However, with the exception of NO_3-N in soil solution in 1990, there were no interaction effects of traffic and tillage on N recovery and losses. Traffic decreased total fertilizer N recovery in the plant–soil system by 17% in 1990, and tended to reduce (10%) N recovery in 1991. The strip-till, subsoiled, and complete tillage treatments applied to cotton were all deep-tilled, and all were observed to have significantly lower NO_3-N concentration in soil solution below the root zone of wheat compared to the surface tillage treatment. In one of the two years (1990), the strip-till treatment increased fertilizer N recovery by 20% in the wheat plant–soil system compared with the other tillage systems applied to cotton. Increased fertilizer N recovery in the plant–soil system and reduced NO_3-

N concentration levels in soil solution measured below the wheat root zone following strip-tillage for cotton suggests that this conservation tillage practice could reduce soil nitrate levels which are susceptible to leaching in multiple-cropping systems. Results from this study also suggest that deep tillage for one crop may decrease N losses from subsequent crops in multiple-cropping systems on coastal plain soils subject to compaction.

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